

Influence of directionality and maximal power output on speech understanding with bone anchored hearing implants in single sided deafness

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Abstract Bone-anchored hearing implants (BAHI) are routinely used to alleviate the effects of the acoustic head shadow in single-sided sensorineural deafness (SSD). In this study, the influence of the directional microphone setting and the maximum power output of the BAHI sound processor on speech understanding in noise in a laboratory setting were investigated. Eight adult BAHI users with SSD participated in this pilot study. Speech understanding in noise was measured using a new Slovak speech-in-noise test in two different spatial settings, either with noise coming from the front and noise from the side of the BAHI ($S_{90}N_0$) or vice versa (S_0N_{90}). In both spatial settings, speech understanding was measured without a BAHI, with a Baha BP100 in omnidirectional mode, with a BP100 in directional mode, with a BP110 power in omnidirectional and with a BP110 power in directional mode. In spatial setting $S_{90}N_0$, speech understanding in noise with either sound processor and in either directional mode was improved by 2.2–2.8 dB ($p = 0.004$ – 0.016). In spatial setting S_0N_{90} , speech understanding in noise was reduced by either BAHI, but was significantly better by 1.0–1.8 dB, if the directional microphone system was activated ($p = 0.046$), when compared to the omnidirectional setting. With the limited number of subjects in this study, no statistically significant differences were found between the two sound processors.

Keywords Bone-anchored hearing aids · Baha · Unilateral hearing loss · BAHI · BP100 · BP110 power · Speech understanding in noise · Single-sided deafness

Introduction

BAHIs are bone conduction hearing aids where sound transmission to the skull and, ultimately, to the inner ear is achieved through a titanium implant behind the ear [1]. BAHIs have been used for over 30 years. They have been shown repeatedly to be beneficial for patients with conductive or mixed hearing loss [e.g. 2, 3], even in the long-term [4].

In addition, BAHIs have been used for more than a decade to compensate for the acoustic head shadow in as single-sided sensorineural deafness (SSD) [5]. Advantages of BAHI in unilateral hearing loss have mainly been documented for adults [6], and even older adults [7]. Especially, in a classroom setting the advantages of hearing aids for children with unilateral hearing loss are well known [8–10].

Until recently, only relatively simple Baha sound processors with only a few possibilities for adjustments were available: the Baha Divino with a user controllable directional microphone system [11] and the Baha Intenso with only one omnidirectional microphone but with a higher maximal power output (MPO) [12]. Today, two more flexible processors, the BP100 [11] and the Baha BP110 power with a higher MPO are available. Both feature a 10-channel audiologist adjustable gain and compression and a directional multi-microphone noise reduction system.

The effect of directional microphone systems on speech understanding with BAHI in users with SSD is complex and not yet fully understood. After the two microphone signals are processed to form a directional system, the

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actual directionality is further modified by the nearby head of the user. Through the output of the BAHI, the processed directional signal is added directly acoustically to the signal, as heard though an unaided ear of the user with its own, individual and frequency-dependent directionality. Furthermore, the BAHI processor is typically slightly tilted laterally due to the rounding of the skull. As BAHIs are placed behind the ear, it is known that more signals can be picked up from the rear than from the front, if an omnidirectional microphone is used [11].

So far, the effect of directional microphones and higher MPO in BAHI users with SSD has been addressed scientifically only in part. Theoretical considerations and preliminary reports suggest that lower transcranial attenuations or, instead of that, BAHIs with higher gains and higher MPO should improve speech understanding in SSD [13, 14]. So far experimental data to confirm this hypothesis remain rare. To our knowledge, the decision between a medium power BAHI or a high power device is handled differently at different centres and possibly on the basis of individual preference.

Regarding SSD and directional microphones in BAHI, there is a study which considers target signal coming only from the front and in which the older Baha Divino is used [15]. It shows the directional microphone to be beneficial. However, it is conceivable, that for noise from the front, such a directional system might actually decrease speech understanding. Meanwhile, a recent study suggests that newer processors (such as the BP100) give more benefit to BAHI users with SSD than the older Baha Divino [16].

The choice of the device with the more beneficial MPO and the adjustment of the device with the more beneficial directionality are of practical relevance to the user.

In this pilot study, we aim to investigate three possible effects of BAHI in SSD with current sound processor technology: (1) the effect of sound processors with higher or lower MPO, (2) the effect of directional microphones in a setting, where BAHIs are expected to provide a benefit, i.e. noise from the front and speech from the side of the BAHI ($S_{90}N_0$) and (3) the effect of directional multi-microphone noise reduction systems when noise comes from the side of the BAHI (S_0N_{90}), i.e. in a setting where BAHIs are expected to be detrimental to speech understanding.

Materials and methods

Subjects

Eight adult subjects, age 29–59, mean 49.1 year, 2 female, 6 male, participated in the study. All had had a substantial sensorineural deafness in one ear for (duration 1–15 years,

mean 7.0 years). They used either a BP100 (6), a Baha Intenso (1), or a Divino (1) on the side of their deaf ear (5 right, 3 left) for 3 months to 4 years (mean 1.3 years). Figure 1 shows a synopsis of their unaided hearing thresholds.

Study devices and fitting

Each participant was fitted with a Cochlear Baha BP100 and with a Cochlear Baha BP110 Power sound processor explicitly for this study. For both sound processors, the first fit suggested by the Cochlear fitting software version 2.0, based on the “BC Direct” threshold measurement [17], performed directly through the processor, was used. The “SSD”-setting of the fitting software, which introduces an attenuation for low frequency signals [18], was chosen. Two program slots were activated. In program 1, microphones were set to “omnidirectional”, in program 2 to “fixed directional”. Position compensation and feedback cancellation were active in both program. In three subjects, feedback occurred with this first fitting with the BP110. It was controlled by reducing the gain above 4,000 Hz in one subject, and by reducing gain at low and at high frequencies in the other two subjects. There were no feedback issues with any fitting of the BP100. Subjects used the

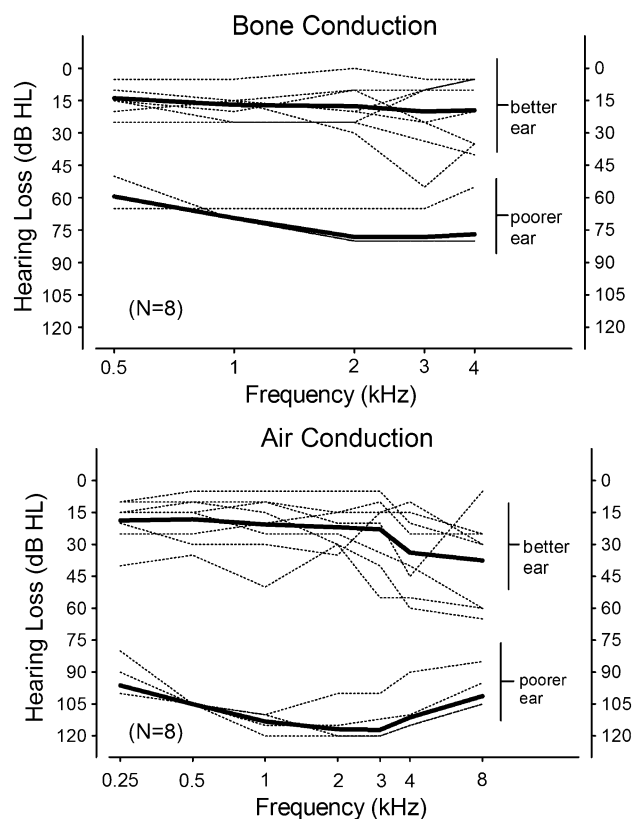


Fig. 1 Bone conduction and air conduction thresholds of the eight study subjects. *Dotted lines* indicate individual measurements and *solid lines* indicate average values

study devices only for the duration of the measurements described in the study protocol below. They were not allowed to keep them after the measurements.

Figure 2 shows examples of transfer functions for a BP100 and a BP110 processor in directional and in the omnidirectional mode from the front and from the side of the BAHl. The measurement was taken in a room of $5.16 \times 5.94 \times 3.40$ m with an average reverberation time of 0.22 s (250–8,000 Hz), and white noise at 70 dBA (71 dB SPL) presented by a loudspeaker (MT160D, Eletttronica Montarbo s.r.l., Bologna, Italy) at a distance of 1 m, resulting in an estimated direct to reverberant ratio of +6.9 dB. The mechanical output signal of the Baha devices was measured by a skull simulator [19]. Both sound processors were programmed on the basis of an assumed direct bone conduction (BC) threshold of 35 dB at all frequencies with P1 in omnidirectional, and P2 in directional mode. Figure 2 shows the relative output of the 8 measurements (2 processor types \times 2 directions of sound arrival \times 2 directionality modes). The 0 dB line denotes the average of all 8 measurements. The differences between the output in the directional and the omnidirectional mode are greater at 90° than at 0° for both sound processors, indicating the directional effect at 90°. There is also a difference between the (higher) output levels of the BP110 and the (lower) levels of the BP100. According to the manufacturer, both processors have roughly the same output for same hearing loss, provided BC thresholds are close to normal (0 dB) and the input levels are reasonably low. However, for combinations of poorer BC thresholds and relatively high input levels, as used here, there may be considerable differences.

Study protocol

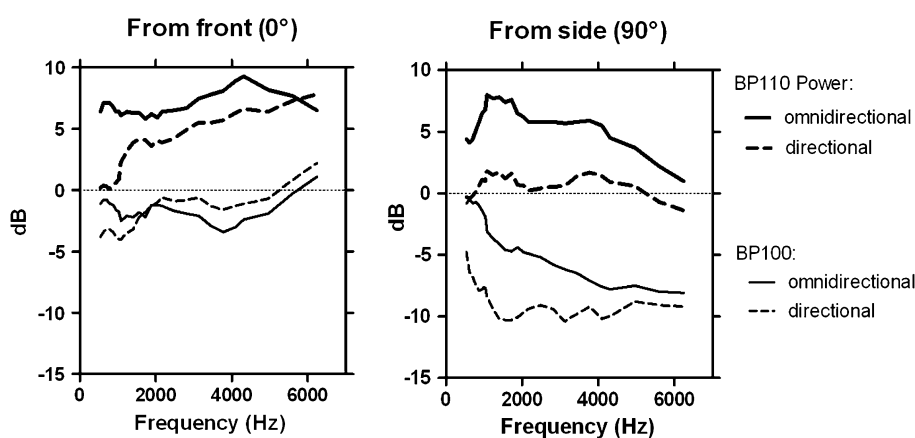
The study has been approved by the ethical committee of the University of Kosice and has been performed in accordance with the Declaration of Helsinki. All participants gave their informed consent prior to inclusion in the study.

After pure tone audiometry (Fig. 1), the transcranial attenuation of each participant was estimated as the difference between the bone conduction thresholds measured without masking with the bone vibrator placed at either side of the head [20]. Then speech-in-noise tests were performed using a novel Slovak test. This test consists of 30 lists of 15 test items, where each test item consists of an introductory phase (“repeat the word...”) and a test word. The test items are presented in the presence of a CCITT (Comité Consultatif International Téléphonique et Télégraphique) speech spectrum noise signal. The noise level is fixed at 70 dBA (72 dB SPL) for the entire test. The level of the first test word in each list is 76 dBA. The level of each following test item is decreased by -2 dB, if the last test word was repeated correctly, or increased by $+2$ dB, if it was not correct. The average presentation level of the last nine test items (7 through 15) plus the level, which would be used for a virtual 16th test item, are averaged to calculate the estimated signal-to-noise ratio (SNR) necessary for 50 % speech understanding. The estimated slope of the discrimination function is 14 %/dB.

All measurements were performed the sound field with speech and noise coming from two spatially separated loudspeakers [21]. Two spatial settings, S_0N_{90} and $S_{90}N_0$ as shown in Fig. 3, were used. The test room at the ENT-Department of the University hospital of Kosice had a volume of 27 m^3 and an almost frequency independent reverberation time of 0.13 s (250–4,000 Hz). Two loudspeakers (Type 1C, Behringer Inc, Willich, Germany) were placed at a distance of 1.2 m in front and at the BAHl side of the subject, respectively. Subjects sat on a chair and were instructed to face the front loudspeaker.

Ten tests in three groups were performed with each subject. Each test consisted of two test lists, the results of which were averaged. In the first group of tests, speech understanding was tested without a BAHl in both spatial settings. In the second group of tests, speech understanding in noise was tested with a BP100 with the directional microphone switched on and off.

Fig. 2 Output of the Baha BP100 and the BP110 power sound processors, as measured at the output of a skull simulator. Acoustic input is white noise at 70 dBA either from the front (0°) or from the side (90°). The 0 dB line in both sub-graphs is the average response of all 8 measurements shown. See text for details. The output is lower for the BP100 and for signals arriving from 90° in the directional mode



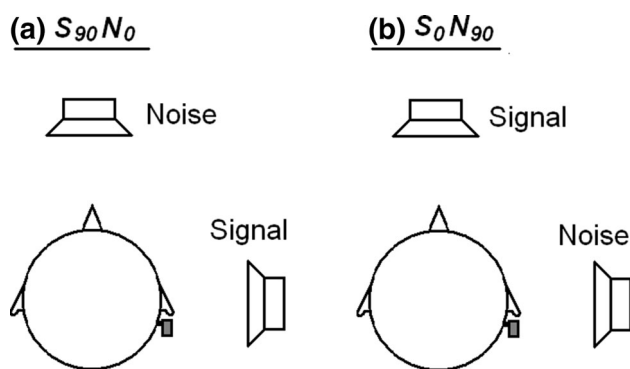


Fig. 3 Schematic representation of the two spatial settings used in the experiments

In the third group, the same tests were performed with the BP110. The order of the groups of tests and the order of the tests within the groups were systematically varied to minimize effects of learning or fatigue. As a consequence, half of the participants were tested first with the BP100, the other half with the BP110 Power.

Statistical analysis

Results were analyzed by a certified statistician (M.K.) using InStat 3.10 (GraphPad Inc., La Jolla, CA, USA) and Past 2.16 (University of Oslo, Norway) for the non-parametric-ANOVA (NP-ANOVA) analysis.

Results

Figure 4 shows the results of the speech-in-noise test. Results are shown as improvement in signal-to noise ratio (SNR) with Baha, when compared to the situation without Baha. Positive values denote an advantage with Baha.

In spatial setting $S_{90}N_0$, there is a statistically significant advantage between 2.2 and 2.8 dB for both speech processors and for both the directional and the omnidirectional microphone settings ($p = 0.004$ – 0.016 , Wilcoxon signed rank test). There is no significant difference between the four conditions tested (Two-way-NP-ANOVA: $p > 0.55$ for both factors and their interaction).

In spatial setting S_0N_{90} , where noise arrives from the side of the BAHI, the expected deterioration in speech understanding due to the BAHI can be found. It is larger and statistically significant if the microphone setting is omnidirectional (-2.0 and -1.7 dB; $p = 0.023$ and 0.039) and smaller and statistically non-significant for the directional setting (-0.2 and -0.7 dB, $p = 0.32$ and 0.16). Two-way NP-ANOVA shows a significant difference for the factor “directionality” ($p = 0.046$) but not for “processor type” or interaction.

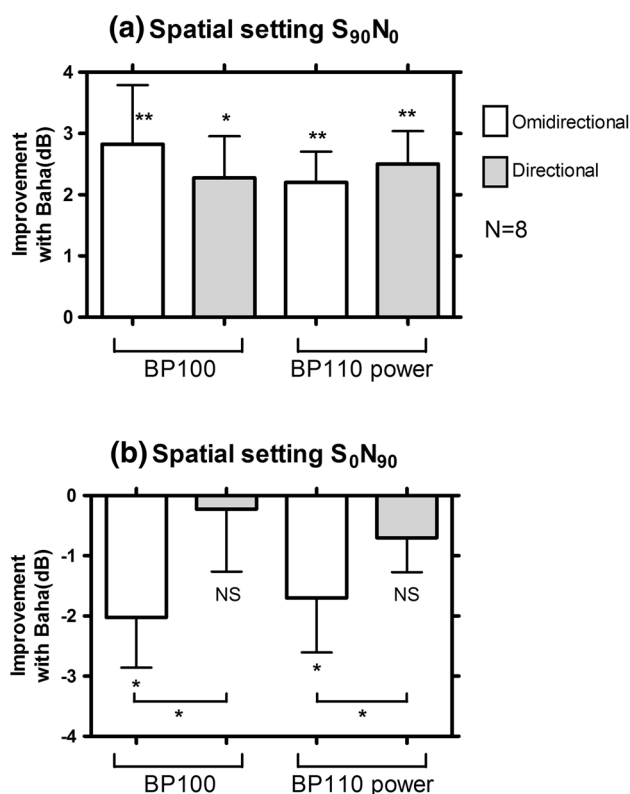


Fig. 4 Speech understanding in noise with two different Baha sound processors (BP100 and BP100 Power), two different spatial settings and two settings for directionality. Average values and standard errors of the mean are shown. The improvement in setting $S_{90}N_0$ is relatively constant across different settings. The deterioration in setting S_0N_{90} is smaller in the directional mode. (NS = difference from 0 is not statistically significant; * $p < 0.05$; ** $p < 0.01$)

It was analyzed, whether any of the effects of a BAHI depicted in Fig. 4 depend systematically on the unaided hearing ability of the subjects. To this end, the (a) average BC thresholds of the better hearing ear and (b) the transcranial attenuation was calculated for each subject over a frequency range of 500–4,000 Hz. Linear correlations between these two parameters and each of the eight improvements or deteriorations due to a BAHI shown in Fig. 4 were calculated. All of the 16 resulting correlation coefficients tended to be low ($r^2 = 0.0005$ – 0.39) and even before corrections for multiple testing, none of the slopes differed significantly from 0 ($p = 0.10$ – 0.96). The highest positive correlations were found between the BC thresholds of the better ears and the gain with the BP100 and the BP110 in the directional mode and the setting $S_{90}N_0$ ($r^2 = 0.25$ and 0.39 ; $p = 0.21$ and 0.10).

Discussion

In several aspects, our data reproduce and confirm results from earlier studies [e.g. 18, 22, 23]. We find a consistent

benefit in terms of speech understanding in noise between 2.2 and 2.8 dB and a smaller, but reproducible disadvantage if noise comes from the side of the BAHl.

The number of subjects in this study was limited by the number of the subjects available at the study centre. As a consequence, the statistical power is also limited. While large effects can be found within this group and can be statistically significant even for $N = 8$, smaller effects may be missed in this study.

The aim of this study was to look for three effects, only one of which (better speech understanding in the directional microphone in the S_0N_{90} setting) was found. The other two effects (a benefit of the BP110 Power over the BP100 and a decrease in speech understanding for the directional mode in $S_{90}N_0$) were not found.

If noise arrives from the side and the target signal from the front, the negative effect of the BAHl can be decreased by 1.0–1.8 dB using a fixed directional microphone. It is conceivable that this positive effect would be larger, if the adaptive directional microphone mode instead of the fixed mode would have been used. The effect can be seen with both speech processors types.

As a side product, these results also show that the fixed directional mode of the BP100 and the BP110 is able to improve speech understanding even for noise from the side, and not only from diffuse noise fields or from the rear [11, 15].

For noise from the front ($S_{90}N_0$), we expected a slight deterioration of speech understanding, when the directionality towards the noise source was activated. However, our data do not show such an effect. Several factors may contribute to this result. First, the overall directionality of hearing of a subject with a good ear and a contralateral BAHl are not well understood and the resulting directional pattern is probably more complex than a simple directionality straight ahead. In addition, the heads of our subjects were not fixed during the experiments. Although we can exclude large head movements, smaller head movements, searching directions with slightly better speech understanding may have taken place. If this is true, we could probably also expect such corrective head movements in real life situations. Finally, the number of subjects available at the University of Kosice for this study was limited. Therefore, the effect may be there, but too small to be detected. One aspect, directionality has in common with other measures in patients with SSD, is that a simple reversal of the positions of the signal and noise source does not result in an equally simple inversion of the SNR required for 50 % speech understanding. This phenomenon is known for the basic benefit of the BAHl, where so far all studies show a greater gain in $S_{90}N_0$ than loss at S_0N_{90} , as well as for low frequency attenuation [18, 22, 23].

We found no difference in speech understanding between the two sound processors. Again, this might be an effect of the small sample, but other explanations appear more plausible. The difference between the two processors emerges predominately for users with poorer BC thresholds. In our study, the BC thresholds of the better ear were, on average, around 15 dB (Fig. 1) and possibly not high enough for the difference to show.

Our group of subjects is not completely homogenous with respect to the BC thresholds of the better ear. Specifically, two of the eight subjects have higher BC thresholds above 2 kHz than the rest of the group (cf. Fig. 1). These two subjects might experience a greater benefit from a more powerful speech processor than the other participants. To test this hypothesis, we compared the results of these two subjects with the average results of the other six subjects. The differences between SNRs with the BP100 and the BP110 Power varied only relatively little, between -0.35 dB (for setting S_0N_{90} , group of six subjects with better BC thresholds) and $+0.25$ dB (for setting $S_{90}N_0$, group of two subjects with poorer BC thresholds).

Transcranial attenuation is known to vary widely between subjects [20, 24]. Frequency-dependent standard deviations of up to 10 dB have been reported [24]. In our analysis at the end of the last section, we have not found any systematic effect of the transcranial attenuation of our subjects on speech understanding in noise with either of the speech processors. The combination of a wide range of transcranial attenuations with a wide range of BC thresholds would not conceal the average benefit of a high power vs. a medium power speech processor, but it would render the group, which benefits most, more difficult to identify.

Furthermore, a benefit of the BP110 power over the BP100 might have been mitigated by feedback issues, which led to lower gains than proposed by the fitting software in three subjects and may have cancelled any advantage. Nevertheless, it is possible that a gain could be found with the BP110 power in subjects with either poorer hearing in the better ear or possibly in users with high transcranial attenuations.

In conclusion, BAHl users with SSD can benefit from a directional microphone setting. In acoustically unfavourable situations, such as the S_0N_{90} setting in this study, SNR is improved by approximately 1.0–1.8 dB. In favourable situations, the gain of 2.2–2.8 dB seems largely independent of the directional setting and of the MPO of the sound processor used. As a consequence, Baha users with SSD might benefit from a selectable or possibly even from a permanent directional noise reduction setting in their everyday environment.

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Conflict of interest Co-author F.P. works part time for the University Hospital of Bern (Inselspital) and part time for Cochlear Inc. The flights of 2 members of the Swiss group to Kosice for the measurements were paid for by Cochlear Inc.

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